

Doping in III–V Semiconductors

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Page 1 of 10

Published online by Cambridge University Press

HANWHA v. MAXEON
IPR2024-01198
HANWHA 1105

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521419192

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First published 1993
This digitally printed first paperback version 2005

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Schubert, E. Fred
Doping in III–V semiconductors / E. Fred Schubert.
p. cm. – (Cambridge studies in semiconductor physics and
microelectronic engineering: 1)
Includes bibliographical references and index.
ISBN 0 521 41919 0
1. Compound semiconductors. 2. Semiconductor doping. I. Title
II. Title: Doping in 3–5 semiconductors. III. Series.
QC611.8.C64S34 1993
621.3815'2–dc20 92-35998 CIP

ISBN-13 978-0-521-41919-2 hardback
ISBN-10 0-521-41919-0 hardback

ISBN-13 978-0-521-01784-8 paperback
ISBN-10 0-521-01784-X paperback

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Foreword

Technology revolutions mark their origin from a single breakthrough such as the demonstration of the transistor. Subsequent technological advances make the revolution a reality. The historical evolution from Si transistor to integrated circuits to high speed computers and telecommunications is one excellent example.

Active workers in the field know each advance represents a major expenditure of time and effort (really ‘blood and sweat’). Progress comes about in a competitive atmosphere involving creative ideas, personality forces and technology prognostications.

We are presently in the midst of the microelectronics revolution. Insatiable demands exist for greater data rates, for consumer electronics and for superior telecommunications. We envision a world of wireless communications, video transmissions and displays, and numerous applications of high speed data transmission. Satisfying this demand is the goal of current research.

For our field of microelectronics this means a systems analysis from the final product to the atomic configurations of the materials that make the product. This analysis itself is remarkable; we can precisely relate the macroscopic system properties – how fast will the system operate – to the microscopic atomic structure – where do the atoms sit in the solid.

Analysis of today’s devices reveal the limitations of today’s semiconductors – mostly silicon. Silicon has been the workhorse for the last thirty years. The ‘silicon community’ continues to squeeze all that is obtainable from this most robust and manufacturable semiconductor. Nevertheless an all silicon technology has foreseeable and predictable limitations.

An electrical engineering student can open almost any textbook and see that the path is clear – III–V semiconductors can do all that Si can do and more – they

emit light! Not only do III–V materials have fundamental characteristics which make faster electronics, but they are efficient emitters and detectors of photons. Combined with a transmission medium – the optical fiber – these III–V semiconductor devices gave rise to the era of optical communications. The intrinsically high speed in an optical system is the basis of our vision of ultra high speed data transmission, yielding electronically controlled visual communications, high definition TV and personal video.

The ‘cost effective’ realization of this technology, on a worldwide basis, depends on our ability to fabricate the materials that make the system. Modern silicon technology demonstrates that basic materials manipulation has governed the advance of the technology. Near perfect crystalline growth, a well behaved passivating oxide, controlled doping, and advanced lithography made the Si revolution a reality. The extension of the semiconductor revolution to III–V devices depends on these materials manipulations, which eventually determine their manufacturability.

Tomorrow’s technology will be based on today’s research; the body of information that allows the ‘systems evaluation’ and meets the ‘manufacturability requirements’. As a starting point a systems evaluation may assume an ideal structure; however, no material is perfect. Better systems evaluation includes far more realistic material configurations and the picture of this realistic material is one goal of the semiconductor materials scientist. Manufacturing requirements will also be determined by this research in terms of yields, process margins, etc.

Both systems and manufacturability evaluations require a deep understanding of the numerous steps that go into the fabrication of a semiconductor. Each of these ‘steps’ becomes a sub-field unto itself – with hundreds of investigators, numerous conferences and publications in an ever expanding network of scientific research.

This book focuses on such an element of III–V devices – the doping of these semiconductors. Basically it addresses the question of the behavior of dopants in III–V semiconductors – how are they incorporated, where do the atoms sit? As explained in the Preface ‘doping’ is an essential element to make an active device from a semiconductor. Clever and controlled manipulation of ‘doping’ can enhance the device properties. Doping processes will be one critical factor in determining manufacturability. Thus the knowledge represented in this book is the critical input needed to provide insight into our technology directions.

One further point, lest it get lost in the current world focus on applied research. Semiconductor science is a field that spans the space of exciting fundamental science to immediate and current applications. Unique solid state structures with controlled doping have revealed new phenomena of the most

fundamental character. Such reports have led to recent Nobel prizes and exciting new concepts. These 'unique solid state' structures combine the latest in materials fabrication and dopant control. Thus, it is worthwhile to note that this slice of science is not only crucial to technology but enables forefront basic research. It has opened the fascinating world of quantum structures and low dimensional configurations.

Those of us who have lived through this semiconductor science revolution look back with pride at the accomplishments of the field and look forward with excitement at what is to come. The science and art of fabricating active III–V semiconductors is a critical element in determining the future.

L. C. Feldman
AT&T Bell Laboratories
January, 1993

Preface

It was realized in the infancy of semiconductor science that impurities are the essential ingredient in these materials. The first usage of the term 'impurities' dates back to 1931 (Wilson, 1931):

Electrons on a foreign atom [in a semiconductor] do not take part directly in [electrical] conduction. They must be transferred by the effect of lattice vibrations to an atom of the pure substance. In this case, the main function of the 'impurities' is to provide electrons for the upper unoccupied energy bands of the crystal, while acting as scatterers is only a secondary function.

The knowledge of the significant consequences of impurities motivated researchers to, first, purify the semiconductor materials, for example by zone refining, and, second, deliberately add 'foreign atoms' to purified semiconductors, for example by thermal diffusion of such 'foreign atoms' into the semiconductor. The deliberate doping of semiconductors with impurities required that the usage of the term 'impurities' was broadened. Such an extended definition was offered by Shockley (1950):

The conductivity arises from the presence of [] atoms which are termed 'impurities', even though added to the otherwise pure [] [semiconductor].

The term 'dopant' was non-existent in the English language until its introduction in 1963 by Seidman and Marshall (1963), who wrote about crystal growth from the melt:

The melt consists of intrinsic polycrystalline Ge and Si mixed with

suitable ‘dopants’ such as P, which produces an n-type melt, or Ga, which produces a p-type melt.

Thus, the term ‘impurities’ is used for unintentional as well as intentional foreign atoms in the semiconductor, while the term ‘dopants’ is used exclusively for deliberately added impurities.

This book is devoted to the many aspects of doping in III–V semiconductors. The book covers, with equal emphasis, fundamental concepts and basic theory of impurities, as well as the practical and technological aspects of the doping process. The basic conceptual theory of shallow impurities and deep levels and their effect on the free carrier concentration is given in Chaps. 1, 2, and 3. Chapters 4, 5, and 6 cover the characteristics of individual impurity elements as well as the doping process during epitaxy with solid elemental sources as well as gaseous sources. Chapter 7 covers characteristics of impurities incorporated during growth, ion implantation, and diffusion, as well as impurity characteristics such as amphotericity, autocompensation, and the maximum attainable doping concentration. Redistribution effects during growth and thermal processing are covered in Chap. 8 and include diffusion, segregation, migration, and other effects. Chapter 9 describes deep levels that are relevant to III–V semiconductor technology, such as the DX-center, EL2, O, Cr, Fe, and rare-earth impurities. Doping in semiconductor microstructures, which require highly controlled doping profiles, is described in Chaps. 10 and 11. Finally, Chap. 12 summarizes electronic, optical, and structural impurity characterization techniques.

The book is written for graduate students, researchers, and development engineers of the disciplines electrical engineering, physics, materials science, and chemistry working at universities, industrial research laboratories, government laboratories and production facilities. It is suited as a textbook for graduate courses in electrical engineering and material science. The book is self-contained and covers all major concepts in detail. Units of the *Système International* (S.I. units) are used throughout the book. Boxes are drawn around those equations which are frequently used in semiconductor science.

The author has benefited significantly from suggestions, discussions and collaborations with his colleagues at AT&T Bell Laboratories, especially with G. A. Baraff, T. Y. Chang, A. Y. Cho, L. C. Feldman, G. H. Gilmer, A. M. Glass, H. J. Gossmann, R. D. Grober, T. D. Harris, W. D. Johnston, Jr., R. F. Kazarinov, R. F. Kopf, M. Lax, A. F. J. Levi, H. S. Luftman, R. M. Lum, R. J. Malik, D. P. Monroe, M. B. Panish, L. Pfeiffer, D. Ritter, S. Schmitt-Rink, H. L. Stormer, V. Swaminathan, W. T. Tsang, J. S. Weiner, and J. L. Zilko. I also thank Professor D. G. Deppe (Univ. Texas, Austin), Professor Y. H. Yao (Univ. Nebraska,

Lincoln), and Professor K. Ploog (Paul Drude Institute, Berlin) for many suggestions and valuable discussions. The encouragement of F. Capasso and D. V. Lang during the course of this work was highly appreciated. I am indebted to L. C. Feldman for writing the foreword.

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February, 1993